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MINERALOGY AND COMPOSITION OF THE UPPER MANTLE

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Abstract. Seismic velocities are calculated for two petrological models of the upper mantle, an olivine-rich assemblage, pyrolite, and a garnet-clinopyroxene rich, olivine bearing, assemblage, piclogite. These are compared with recent seismic profiles for various tectonic provinces. The shield data is most consistent with a cold olivine and orthopyroxene-rich LID (the seismic lithosphere) extending to 150 km followed by a high temperature gradient and/or a change in mineralogy that serves to decrease the velocity. From 200 to 400 km the velocities follow a 1400°C adiabat. The rise-tectonic mantle is much slower, presumably hotter and is likely to be above the solidus to depths of at least 300 km. The high V_p/V_s ratio of the lower oceanic lithosphere in the western Pacific is most consistent with eclogite.

Introduction

Large lateral variations in seismic velocities and the effects of high temperature gradients, anisotropy and partial melting have made it difficult to infer the composition and mineralogy of the upper 400 km of the mantle. The important minerals in this region of the mantle are undoubtedly olivine, orthopyroxene, clinopyroxene and garnet and the dominant rock types are presumably harzburgites, lherzolites, pyroxenites and eclogites. The composition and mineralogy may change both vertically and laterally. At depths between 200 km and the 400 km discontinuity the average velocities are generally consistent with either peridotite or eclogite while those between 400 and 670 km are more consistent with an olivine eclogite, or piclogite, assemblage [Bass and Anderson, 1984]. The large lateral variations in velocity above 400 km [Nataf et al., 1984; Anderson, 1984] may be due to differences in petrology, temperature or crystal orientation.

In this paper we compute seismic velocities as a function of temperature and pressure for two representative mineral assemblages using the elastic constant data summarized by Bass and Anderson [1984 and paper in preparation].

Pyrolite is a hypothetical olivine-rich rock which can yield tholeiitic magmas by about 25% partial melting [Ringwood, 1975]. We define piclogite as an olivine eclogite, the high pressure form of picrite. It is a clinopyroxene-garnet rich, olivine-bearing rock which may be complementary to or derivative from more ultrabasic assemblages. It is not meant to refer to a specific mineralogy or composition but is used in the same general sense as the terms basalts, picrites and eclogites are used. We compare the results for these two rock types with recent seismic velocity distributions for the upper mantle beneath several distinct tectonic regions including shield, rise-tectonic and oceanic areas.

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Procedure

The elastic constant data and the mineralogy of pyrolite and piclogite assemblages are summarized in Table 1. The P = 0 densities and velocities are calculated at various temperatures assuming a linear temperature dependence of bulk modulus, K, rigidity, μ, and thermal expansivity, α. These high temperature values are then used in the finite strain equations of Sammis et al. [1970] to calculate $V_p, V_s, \rho, V_p/V_s$ and $\Phi (= K/\rho = V_p^2 - (4/3)V_s^2$ along various adiabats. Figure 1 gives the results for compressional velocity, V_p, and shear velocity, V_s for the olivine-rich (pyrolite), and garnet-clinopyroxene rich (piclogite) assemblages. We assume that the mineralogy does not change with depth or temperature. The effects of pyroxene-garnet reactions will be discussed later.

At depths shallower than 200 km, V_p is lower for pyrolite but pyrolite and piclogite have similar V_s. At greater depth the compressional velocities converge but pyrolite V_s is greater than the predicted V_s for piclogite. The difference in trend between the two assemblages is caused mainly by the different bulk moduli and pressure derivatives. These curves suggest that V_p is the better mineralogical discriminant above 200 km, whereas V_s is more strongly affected by temperature and is insensitive to mineralogy. These roles are reversed below 200 km.

The parameter V_p/V_s, related to Poisson's ratio, is a very weak function of temperature. Figure 2 shows V_p/V_s which, for the parameters chosen, is nearly independent of temperature for piclogite and weakly dependent on temperature for pyrolite. V_p/V_s is, therefore, a good mineralogical discriminant. It is less than 1.71 for forsterite, jadeite and orthopyroxene and greater than 1.76 for clinopyroxene and garnet. Eclogites and piclogite therefore have relatively high V_p/V_s compared to peridotites.

The seismic parameter $\Phi (=K/\rho)$ depends both on temperature and composition but because it is independent of the rigidity it should be relatively insensitive to high temperature effects such as partial melting and dislocation relaxation. Both K and ρ decrease slightly upon partial melting.

Figure 1 also shows an estimate of the solidus temperature of the mantle [Wyllie, 1984]. The 1400° and 1800°C adiabats, for example, are in the partial melt field at depths shallower than about 100 and 300 km, respectively. Partial melting reduces the velocity from the values calculated [Anderson and Sammis 1970, Anderson and Spetzler, 1970]. Dislocation relaxation effects

TABLE 1. Composition and Properties of Two Mineral Assemblages

	Pyrolite	Piclogite	V_p/V_s
Olivine (wt.pct.)	57	16	1.73
Orthopyroxene (wt.pct.)	17	6	1.67
Clinopyroxene (wt.pct.)	12	33	1.74
Garnet (wt.pct.)	14	45	1.80
$\rho(g/cm^3)$	3.379	3.497	
V_p(Km/sec)	8.306	8.445	
V_s(km/sec)	4.801	4.800	
dK/dP	5.3	4.8	
$d\mu/dP$	1.9	1.7	
dK/dt(kb/^{o}C)	-0.20	-0.22	
$d\mu/dt$(kb/^{o}C)	-0.12	-0.12	
$\alpha(10^{-6}/^oC)$	2.6	2.6	
$d\alpha/dt(10^{-8}/^oC^2)$	1.3	1.3	
V_p/V_s	1.730	1.759	

reduce the shear modulus at somewhat lower temperatures [Minster and Anderson, 1981].

Seismic Models

Compressional and shear velocities for shields [Given and Helmberger 1980, Grand and Helmberger 1984a] are shown in Figure 1. Unfortunately, the V_p and V_s data are not for the same regions. The velocities are relatively high to depths of about 150 km and then drop rapidly. The high velocity layer is sometimes called the seismic lithosphere or LID. Below 200 km the velocities fall near the 1400^{o}C adiabat. The trend of V_s between 200 and 400 km parallels the trends of the piclogite adiabats but both pyrolite and piclogite are generally compatible with the data, particularly considering the uncertainties in the pressure derivatives and the possibility of a superadiabatic gradient in this region. The rapid drop in velocity between 140 and 170 km requires a high temperature gradient or a decrease in the olivine content and an increase in the pyroxene content of the mantle. The V_p/V_s ratio for the shield data (Figure 2), is very low in the upper 150 km. Increasing the olivine and orthopyroxene content or decreasing the FeO content of the shield LID, relative to pyrolite, would decrease V_p/V_s. Increasing orthopyroxene, however, would decrease V_p. Therefore, the seismic properties of the shield lithosphere are best explained by a very olivine-rich, possibly low FeO, peridotite with low temperatures and a low temperature gradient. For a uniform harzburgite composition LID the inferred temperature gradient is only about 2-4^o/km, substantially less than the average values of 8-10^o/km expected for a conductive geotherm over the same depth interval. The subsequent rapid drop in velocity, if due to temperature alone, requires a gradient of at least 10 to 14^{o}C/km. The large increase in V_p/V_s with depth suggests that a change in mineralogy is also involved, i.e. an increase in garnet and clinopyroxene relative to olivine and orthopyroxene.

The tectonic-rise model, [Grand and Helmberger, 1984a; Walck, 1984] appropriate for the northern part of the East Pacific Rise, Gulf of California and southern California is dramatically different. The temperatures implied for the upper 300 km are above the solidus and partial melting is suggested. V_p/V_s is also higher than appropriate for any plausible mineral or mineral assemblage. V_p/V_s is particularly high between 75 and 200 km, suggesting that melting is a maximum in this depth interval. Although the velocities are low between 200 and about 400 km, the velocity gradient is high. The high velocity gradient implies a negative temperature gradient, chemical inhomogeneity, mineral and/or melt reactions or a subsolidus relaxation mechanism that is suppressed by pressure. Both pyrolite and piclogite satisfy V_p near 400 km for the 1400^{o}C adiabat. The average temperature difference between the seismic models appears to be about 400^{o}C or less between 300 and 400 km.

The inferred temperature for the oceanic profiles is above the solidus for most of the mantle above 300 km. The melting curve, of course, is not well known below depths of about 100 km and is an extrapolation from measurements at low pressure. Velocities are still low below 300 km and the V_p/V_s ratio is high for the ridge-tectonic profile. If the solidus curve is some 300^{o}C lower than shown at 400 km then the low velocities and high gradients between 300 and 400 km could be due to a decreasing amount of melt with depth. In some tectonic regions high electrical conductivity occurs at these depths and partial melting seems to be required [e.g. Roberts, 1983].

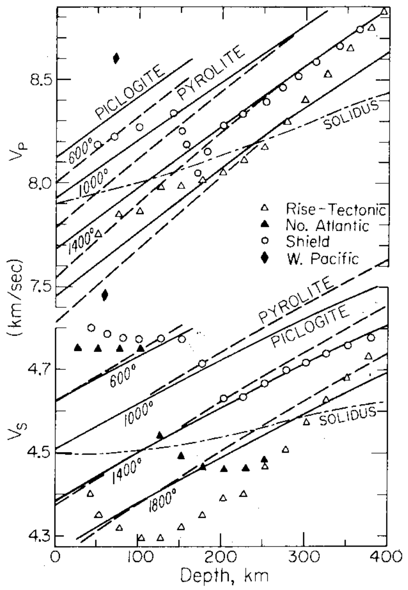

Fig. 1. Compressional and shear velocities for pyrolite and piclogite along various adiabats. The temperatures are for P = 0. The solidus curves are from Wyllie [1984]. The portions of the adiabats below the solidus curves are in the partial melt field. The seismic profiles are for shields [Given and Helmberger, 1981; Walck, 1984], tectonic-rise [Grand and Helmberger, 1984a, Walck, 1984], and the North Atlantic [Grand and Helmberger, 1984b] regions. Pacific ocean data are from Shimamura et al. [1977].

The V_s structure for the northwest Atlantic [Grand and Helmberger, 1984b] lies between the shield and rise models. Partial melting or some other high-temperature relaxation mechanism is implied for the region between 130 and 300 km. The mantle beneath the northwest Atlantic is similar to the rise mantle between 250 and 400 km.

The inferred high olivine content for shield lithosphere agrees with evidence from kimberlite xenoliths. However, an olivine-rich lithosphere is not necessarily appropriate for other regions. Although data is extremely limited, the high V_p/V_s and Φ of the lower oceanic lithosphere are more compatible with a garnet-rich assemblage such as eclogite, [Anderson, 1977, Shimamura et al. 1977, Sumino and Nishizawa, 1978]. This implies that the oceanic lithosphere is much denser than the shield lithosphere, consistent with the instability of the former and the long-term stability of the latter. Eclogite is stable in the oceanic lithosphere at depths on the order of 50 km. The freezing and cooling of basaltic melt at depth is one mechanism for forming eclogitic lithosphere. There is no particular reason for assuming that all the basaltic melt in the mantle emerges at ridges to form oceanic crust.

Effect of Pyroxene-majorite Transformation

The calculations described above assume that the mineralogy does not change with depth. However, in the pressure range of interest there is a gradual transformation of pyroxene to majorite. This effect is small for the pyrolite mineralogy because of the small total amount of pyroxene. An approximate allowance for this effect using methods described in Bass and Anderson [in preparation] gives velocity-depth curves slightly steeper than shown. The calculated increase in velocity at 400 km corresponds approximately to a decrease of 100-200°C in the temperature of the constant mineralogy cases (Figure 1). Therefore, when the pyroxene-majorite transformation is taken into account the inferred temperature of a pyrolite mantle is slightly warmer.

The effect of a pyroxene-garnet reaction is much larger for the piclogite mineralogy. When the pyroxene-majorite transformation is taken into account the velocities are higher than shown and the velocity gradients are similar to those calculated for pyrolite. A starting piclogite mineralogy with 22 wt.% olivine, 43% cpx and 30% garnet gives results which fall close to the pyrolite adiabats in Figure 1. These preliminary calculations illustrate the tradeoffs between mineralogy, phase changes and temperature.

Discussion

The present results combined with those of Bass and Anderson [1984] regarding a piclogitic transition zone are consistent with the following scenerio. Material in the transition zone becomes buoyant because of high temperature, partial melting or because it is displaced by subducted material, and rises into the shallow mantle. Melting is most extensive under ridges at about 100 km depth. Crystal fractionation yields picritic or tholeiitic melts which emerge at midocean ridges and underplate the oceanic lithosphere, leaving behind olivine, clinopyroxene or garnet-rich cumulates, depending on depth.

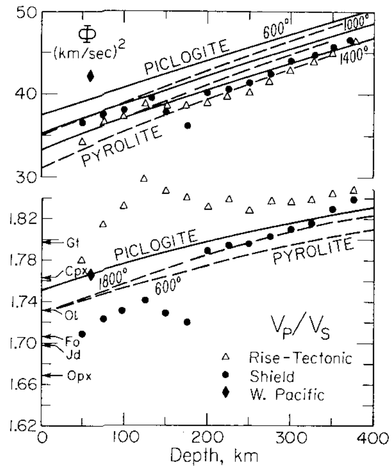

Fig. 2. Seismic parameter and V_p/V_s for two petrological models and various seismic models. See caption to Figure 1 for data sources.

The thickness of the rising sheets, and the depth extent of the eclogite portion of the lithosphere, are unknown but may be considerable. The low velocities associated with ridges must extend over a wide zone since they affect surface waves of long wavelength and body waves travelling well off-axis of the ridge. Similarly, the high velocities associated with subducted material may extend over a width of 100-150 km [Hirahara, 1977, 1981]. An oceanic lithosphere thickening by the addition of eclogite or picrite at its base satisfies a variety of geophysical and petrological data [Ito, 1974].

Surface waves and shear waves, the main tools which have been used to probe the upper mantle in inaccessible areas such as oceans, cannot discriminate between olivine-rich and clinopyroxene-and garnet-rich assemblages in the lithosphere and underlying mantle. For V_p there is a trade-off between temperature and mineralogy but for reasonable temperatures the high V_p reported below 50 km in some oceanic regions and the high oceanic V_p/V_s ratio favor a garnet-rich assemblage for the lower oceanic lithosphere. The composition of oceanic mantle between about 50 or 100 km, depending on age, and 400 km, is undetermined because of the obvious intervention of relaxation or partial melting effects, the general similarity of predicted profiles for various mineralogies and the trade-offs between composition and temperature.

Neither olivine-rich materials such as pyrolite nor clinopyroxene and garnet-rich assemblages, such as piclogite, can be ruled out as important constituents of the upper mantle. An olivine-rich assemblage is supported on the basis of velocity, anisotropy and direct sampling for the shield lithosphere and the immediately sub-Moho oceanic layer. Olivine is buoyant relative to undepleted, garnet-rich lherzolite or eclogite and can therefore be expected to preferentially concentrate in the shallow mantle. Density increases in the order basalt, peridotite, eclogite which is the sequence suggested above. The high velocity gradients in the oceanic mantle below a depth of 100 to 200 km may be due to decreasing amounts of melt with depth. Although there may be peridotite-rich regions between 100 and 400 km under oceans and between 200 and 400 km under shields the present results show that the seismic data do not demand such an interpretation. The mineralogy of the deep lithosphere and underlying mantle may ultimately be deduced on the basis of the V_p/V_s ratio.

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